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THE GALACTIC ORIGIN OF COSMIC RAYS II

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ABSTRACT

The CR acceleration due to shocks in the ISM depends upon multiple crossings $\cong c/3\ v_{Alfvén} \cong 10^4$ per e-fold energy gain. The up-stream scattering required to produce this barrier is Alfvén wave turbulence. When the ratio (CR pressure)/$(B^2/8\pi) \equiv \beta > 1$, the streaming velocity theoretically and observationally becomes $\gg v_{Alfvén}$ and, hence, no effective up-stream barrier is likely to exist. If all ISM shock acceleration is limited to $\beta \lesssim 1$ and the average galactic CR condition is $\beta \cong 1$, then shocks in the ISM are unlikely to supply the necessary acceleration. This is particularly so for high energy CR's accelerated early in the remnant history where β must be large and the number of e-folds required are large.

High energy CR's can be produced by the shock breaking out of the envelope into the magnetosphere of the SN star for $E \geq 10^{13}$ to 10^{14} eV. It is usually assumed that the energy dependent escape from the Galaxy $E \gtrsim 10^{15}$ eV produces a steeper spectrum from 10^{15} to 10^{18} eV. Above this energy SN's in all galaxies fill the meta galaxy with CR's with a flatter slope. Conversely, an external source that attempts to fill the Galaxy from the outside must have a still steeper spectrum $\Delta\Gamma \cong -.75$ to penetrate the diffusive barrier of our galaxy yet maintain the observed slope. This is unlikely since the energy density at 10^{15} eV in the meta galaxy would be between 10^{1} to 10^{2} of CR's in this galaxy or of the order of 10^3 of the energy density of particles and fields in the IGM.

1. Introduction

In a companion paper, OG 4-17, the experimental evidence is discussed of the fast escape of ionized matter from a bubble blown in the earth's magnetic field by a high altitude nuclear explosion. In this case, the conditions of adiabatic deceleration and trapping were well satisfied but did not occur, presumably because the particle pressure exceeded the field pressure. As discussed later, this is also predicted by theory. The consequence of this theory is that the acceleration of high energy cosmic rays by shocks in the interstellar medium is inhibited. Conversely, sufficient extragalactic acceleration of high energy CR's is unlikely because of the spectrum expected after diffusion into the Galaxy as well as the implied energy density in the ISM. The consequences of the high β limit to Alfvén wave trapping for shocks in the ISM is discussed in Sec. 2 and the high energy spectrum in Sec. 3.

2 Cosmic Ray Pressure Limit to Cosmic Ray Acceleration in the ISM

The criteria for the Alfvén speed limit to particle streaming velocity is shown by Holman et al (1979) to be equality between particle pressure and field pressure. It is also assumed in the CR-ISM shock acceleration that every particle once crossing ahead of the shock <u>always</u> returns and the only loss is convection down stream away from the shock and this loss determines the spectrum (Bell 1978; Blanford and Ostriker 1978, 1980). The assumption of no loss ahead is based again upon Alfvén wave excitation by streaming because tortuosity has too large a scale $\gtrsim$ 100 pc (Heiles, 1976) compared to the remnant size also $\lesssim$ 100 pc. One has to ask if the ratio of cosmic-ray-pressure/magnetic-field-pressure, $\beta > 1$, whether the streaming velocity ahead of the shock could exceed the shock velocity and the particles escape ahead of the shock. One must remember that the number of trials of this question per e-fold of energy gain is immensely large. From Bell (1978), this number, $N_{efold} = 3/4\ \eta c/v_{shock}$. Here η is the compression ratio that must be greater than 3 to create an adequate spectral index. Hence $N_{efold} \gtrsim 10^4$ when $v_{shock} \to 10^7$ cm s^{-1} at the maximum extent of the shock, assuming $v_{Alfvén} \cong 3 \times 10^6$ cm s^{-1} in the ISM. The streaming velocity as a function of β has not been adequately investigated, but it would seem unlikely given this large number of trails per e-fold that β must be even as large as unity for the streaming loss ahead of the shock to be comparable to that behind. If β is indeed limited to unity in the medium ahead of the shock, we can ask whether the energy input by ISM shocks, i.e., the total supernova shock remnant volume $\times B^2/8\pi$ per cosmic ray age is large enough to accelerate the cosmic-ray energy. We already know that the Galactic cosmic-ray energy density is roughly the same as the magnetic energy density and may even exceed it by several fold which should be impossible to achieve on this model, but assuming they are equal, we require that the mean total remnant volume swept out in the cosmic ray age equals the total cosmic-ray galaxy volume. There is no advantage in assuming a large fraction of the remnant volume is in low density "tunnels" because here we must assume an equally low value of B or worse, a lower value of B^2. Hence, the most conservative assumption is the mean density from cosmic-ray age and spallation is $\langle n_p \rangle = 0.3$ cm^{-3} (Cesarsky 1980) and choosing $\langle B \rangle = 3 \times 10^{-6}$ gauss, $v_{Alfvén} = 10^6$ cm s^{-1}. Under these conditions, the radiative phase of the remnant starts earlier, $\cong$ 33 Pc (McCray and Snow 1979) and a smaller size of the useful shock remnant ensues $\cong$ 50 pc rather than 100 pc assumed by Blanford and Ostriker (1980) for the low density tunnel regions. Then the condition $\beta = 1$ limits the incremental energy to $\leq B^2/8\pi \cong 4 \times 10^{-13}$ ergs cm^{-3}, $B \lesssim 3 \times 10^{-6}$ gauss and the energy input per SN becomes $\lesssim 5 \times 10^{48}$ ergs. This would be a marginal energy input. The effect of regions of reduced field in tunnels, or a limit on $\beta < 1$ due to the necessary many shock crossing trials would further reduce this energy input. In summary, the $\beta = 1$ Alfvén speed streaming limit imposes a new and strong constraint on SN-ISM shock models of cosmic-ray acceleration and a more detailed analysis is required to substantiate the present optimistic view.

3. Ultra High Energy Cosmic Rays

There has been no claim that the supernova shock in the ISM acceleration mechanism can give rise to cosmic rays where energy is greater than $\cong 10^{15}$ eV or less, 10^{12} eV (Blanford and Ostriker 1980) again because of the number of shock crossings required as well as a limiting Lamor radius. Hence, the spectrum above 10^{15} eV and possibly as low as 10^{12} eV must be due to another mechanism.

We point out that if the origin is extra galactic, then the source spectrum must be very strange indeed and somehow fortuitously match the internal generated flux without a large singularity in slope.

If cosmic rays find it increasingly easy to diffuse out of the Galaxy as their energy increases, then an external source must find it more difficult to diffuse into the galaxy at lower energies. The steepening of the observed spectrum between 10^{15} eV and 10^{18} eV (Watson 1930 and Cunningham et al 1980) is well explained by Bell, Kota and Wolfendale (1974) as the decreased scattering of cosmic rays as a function of energy by the magnetic inhomogeneity of H clouds in the Galaxy. An external source would experience an inverse problem in trying to diffuse into the Galaxy. Here the destruction lifetime within the Galaxy compared to the diffusion lifetime out becomes the pertinent parameter. Since at 10^{15} eV the two times are comparable, we would expect that an external source spectrum index would be flattened by roughly the same amount as an internal source would be steepened. The latter value (integral spectrum) is $\Delta\Gamma \cong -0.75$ giving an index $\Gamma \cong -2.45$. Consequently, an external source would have to have a spectral index of $\Gamma_{observed} + \Delta\Gamma \cong -3.2$. At the same time above 10^{18} to 10^{19} eV the external source would require the observed slope of $\Gamma \cong -1.31$. Thus, the external source would be required to have fortuitously a major change of slope $\Delta\Gamma \cong 1.9$ just at the peculiar energy where direct escape of cosmic rays from the Galaxy becomes possible. This seems very unlikely, especially when one considers that in addition, the fluxes must match at 10^{15} eV where the diffusion loss becomes significantly less energy dependent. Aside from the unlikely nature of a spectrum as steep as (integral) of $\Gamma = -3.2$, there arises a serious problem with the energy density in the IGM. Let us suppose in order to minimize the problem, that below 10^{15} eV the meta galactic source cuts off and that CR's below 10^{15} eV are galactic in origin. Then the energy density of CR's in the IGM will be larger than in the Galaxy ISM at 10^{15} eV by the ratio $(10^{18}/10^{15})^{\Delta\Gamma}$ $\cong 10^{2.25}$. But the Galactic energy density at 10^{15} eV is $\varepsilon_{ISM\ 15} = \varepsilon_{ISM,\ 0}\ (10^{15}/10^{9})^{1-\Gamma} \cong 10^{-3.7}\ \varepsilon_{ISM-0}$; $\varepsilon_{ISM,0}$ = CR energy in the Galaxy. Hence, $\varepsilon_{IGM} \gtrsim 10^{-1.5}\ \varepsilon_{ISM,0}$. This is at least 10^3 times the likely value of $B^2/8\pi$ in the IGM and, hence, is most unlikely. One is then forced to consider that CR's up to at least 10^{18} eV are formed in the Galaxy. It would seem far simpler to have one source for all energies within all galaxies. If this source flattens in slope by $\Delta\Gamma \cong +0.4$ above 10^{13} to 10^{14} eV as expected from SN ejecta, then the progressively easier escape from the galaxy above 10^{15} eV $\Delta\Gamma \cong -1.0$ produces the steeper observed spectrum and above 10^{18} to 10^{19} eV the loss from all galaxies fills the meta galaxy to the level of the flux observed 10^{19} to 10^{20} eV (Colgate 1974). This is the current picture of the spectrum and flux produced by the shock ejection of the envelope of Type I supernova.

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